Current Transducer : Thermal Simulation validated by Measurements

Bernard Richard, LEM Components, Switzerland
e-mail: bri@lem.com

1. Abstract

To know the thermal behavior of current transducers require to define the current measurement range, to optimize the thermal distribution of each components (parts stress analysis) and to set the environmental thermal limitations.
Thermal analysis can be pragmatic (thermal measurements on existing samples) or theoretic (thermal simulations).
The advantage of the latter is the flexibility to change the parameters (e.g. primary current, ambient temperature, AC or DC behavior) and to get quickly the new thermal distribution, allowing a fine tuning of the design before any hardware prototype is made.
Nevertheless, such approach is only effective if the calculation results are accurate and reliable, and many practical factors and assumptions make it generally difficult. Those factors are addressed hereunder.

2. Thermal description of the transducer

2.1 Power sources

For the closed loop transducer, several thermal heating sources exist :

- Secondary winding (2 [W])
- Primary conductor
- Transistors of the push-pull output stage (die and pins) (1 [W])
- PCB tracks which carry the secondary current of the transducer (53 [μW])
- Magnetic core

Power values given in bracket correspond to the paragraph III simulated cases.
The power in the pins and the PCB tracks could be neglected. But it's important to model the tracks for the thermal dissipation.
At high frequency, eddy currents appear in the magnetic core and generate iron losses. For the closed loop transducer, the flux is compensated and consequently the iron losses at low frequency are negligible : it will not be taken into account for this modeling.
Nevertheless, with the adequate magneto dynamic simulation tool, it would be possible to calculate the iron losses at high frequency and to include this power source in the thermal simulations.

2.2 Principle of the modeling

To make this simulation, all the areas with losses are described by a power density. An equivalent resistance R of each component is estimated and the corresponding resistive losses calculated with the formula $R I^2$. For the electric current carriers, it is assumed that the current is homogeneously distributed, in the PCB tracks and secondary winding.
The first difficulty is to determine the equivalent resistance of each component in order to calculate the losses. At the beginning of the modeling, the internal temperature of the transducer is unknown; for this reason, an initial internal temperature is chosen to calculate the losses. For example with an ambient temperature of 70 [°C] or 85 [°C], all the resistances are calculated at 100 [°C] to start the simulation.
After the first iteration, the temperatures used for the losses calculation are compared with the calculation and; if the difference is too large, another iterations are necessary. In this case, the resistance and then the losses are calculated with the temperatures obtained by simulation.

The following parts of the transducer are described :

- Secondary winding (without insulation between wires)
- Magnetic core (without lamination and iron losses)
- Transistors (die, case, pin)
- Transducer PCB with transistor tracks (emitter and collector)
- Transducer case
- Product molding, filling the case.
- The primary conductor is simulated by an isotherm of 100 °C around the hole

2.3 Transistor model

The geometry of the transistor is also estimated and has been validated by comparison between datasheet inputs and simulation. The bounding of the dies not take into account and the die is placed directly on the gold support.

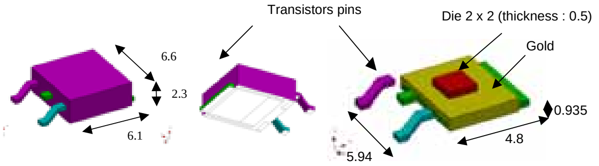

Fig 1. Transistor modeling.

For the die, the power is directly obtained with the following relation :

$$P_{die} = U_{\sup ply\ \max} I_{sn} - (R_c + R_s + R_M) I_{sn}^2 \quad [W]$$

where :

$U_{supply\ max}$: Voltage max of the power supply [V]
I_{sn} : Secondary nominal current [A]
R_c : Equivalent collector resistance [Ω]
R_s : Secondary resistance [Ω]
R_M : Burden resistance [Ω]

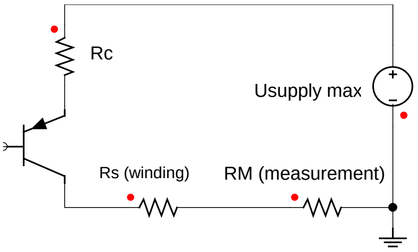

Fig 2. Schematic to calculate the power in the transistor

The push-pull is build with three transistors in parallel. For the DC behavior, only the superior or inferior part of the push-pull is in function (depending on the DC current direction). For AC behavior all transistors are working for half period each.

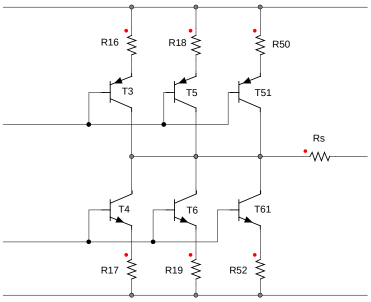

Fig 3. Power stage of the electronic.

Like these transistors are the hot points of the transducer they are the critical parts to control following the customer application.

2.4 Thermal conductivity

For the transducer magnetic core and to determine the conductivity of the core's alloy Fe-Si, it's possible to consider a block formed by one layer of 96 % iron and one layer of 4 % Si. Anisotropic conductivity value due to lamination presence is not taken into account.
The equivalent conductivity is determined with the following relation :

$$K_{eq} = \frac{K_{Fe} K_{Si}}{K_{Fe}\varepsilon + K_{Si}(1-\varepsilon)} =$$

$$\frac{80.4 * 149}{80.4\frac{4}{100} + 149 * \left(1 - \frac{4}{100}\right)} = 81.91 \quad [W\ K^{-1} m^{-1}]$$

For other transducers parts, the conduction coefficients used in the model are given below :

Material	K [W K^{-1} m^{-1}]
Potting material	0.3
Air	0.025
Transistor case	0.15
Copper	401
Gold	318
Epoxy FR4	0.28
Magnetic core (Fe-Si 4%)	81.91
Transducer case	0.17
Die (assumption die is 100% Si)	149

Measurements are made by placing the transducer in an oven with air mixing in order to adjust the temperature. The manufacturer gives a forced convection factor around 13 [W$K^{-1}$$m^{-2}$]. Consequently, the external exchange is simulated with a forced convection coefficient :

$$\alpha = 13 + 0.05 * (T_1 - T_a) \quad [W\ K^{-1}\ m^{-2}]$$

Where T_1 is the surface temperature
T_a is the ambient temperature

3. Thermal modeling result

Figure 10 and 11 show pictures of the hardware and the corresponding simulation results. More details are given hereunder.

3.1 DC modeling results (Tamb = 86 °C)

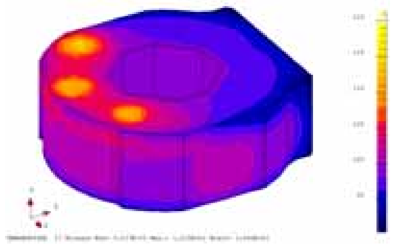

Fig 4. Temperature distribution inside the transducer.

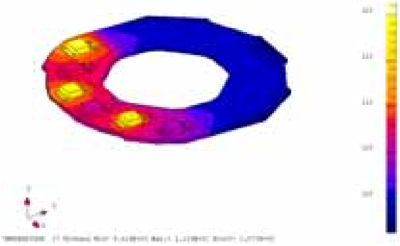

Fig 5. Temperature distribution on the PCB.

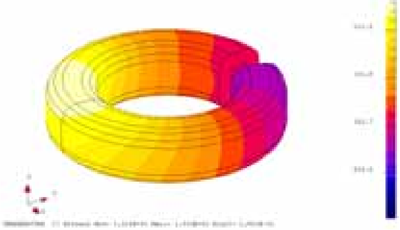

Fig 6. Temperature distribution in the secondary winding

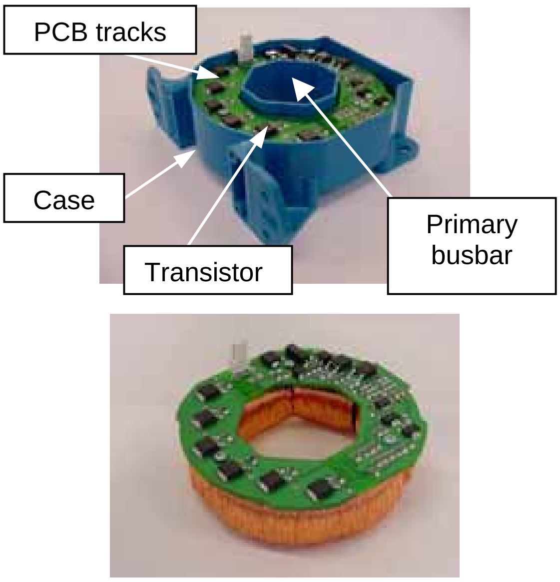

Fig 10. Transducer before filling the case with the product molding.

3.2 AC modeling results (Tamb = 86 °C)

The simulation is made with a low frequency current (no iron losses in the magnetic core). If we consider the iron losses, the temperature of the magnetic core and the winding will change.

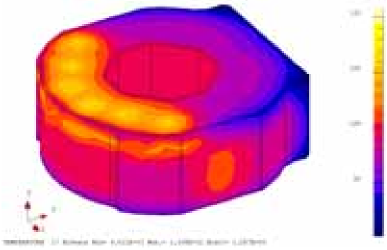

Fig 7. Temperature distribution inside the transducer.

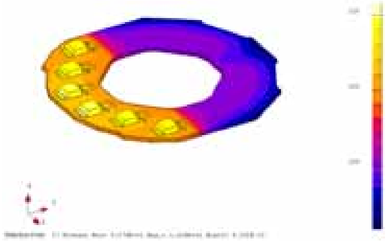

Fig 8. Temperature distribution on the PCB.

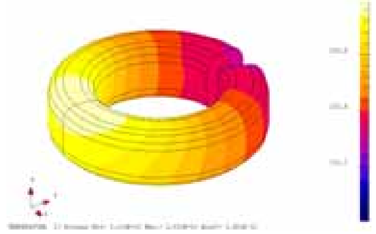

Fig 9. Temperature distribution in the secondary winding.

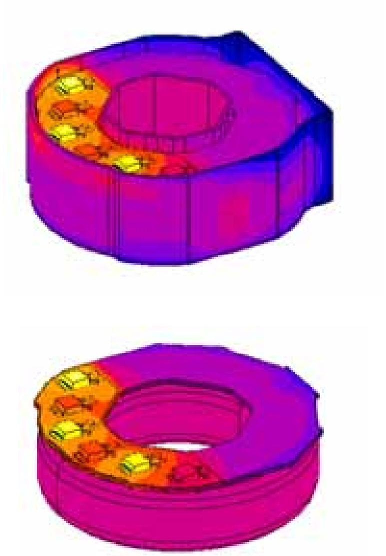

Fig 11. Thermal simulation of the transducer.

4. DC measurements results

The measurements have been done with a DC primary current. Thermocouples are placed inside the transducer before potting.

The transducer is placed in an oven with temperature adjustment.

A primary busbar in aluminum fill the hole and his temperature is kept at a constant 100 °C, to simulate a real primary conductor.

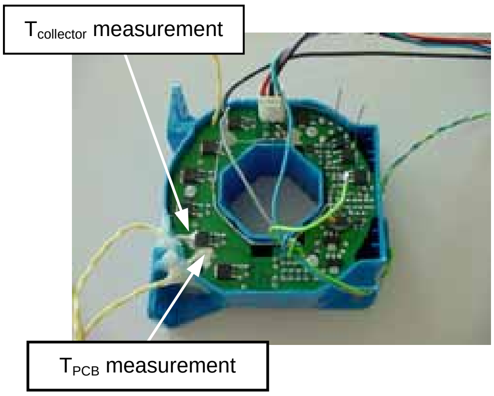

Fig 12. Transducer with thermocouple before potting.

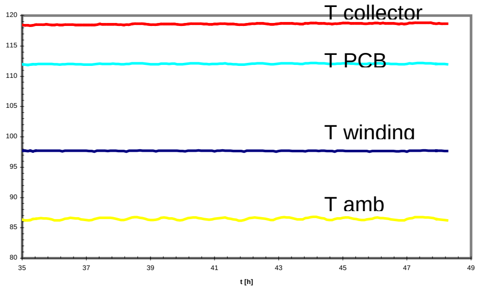

Fig 13. Temperatures measurements with Tamb = 86 °C.

5. Comparisons between measurements and simulations

T amb [°C]	Thermocouple T winding [°C]	Simulation T winding [°C]	Thermocouple T collector [°C]	Simulation T collector [°C]	Thermocouple T PCB [°C]	Simulation T PCB [°C]
27	65	71.81	81	89.00	75	76.40
42	72	79.86	90	97.14	83	84.41
50	76	84.11	95	101.45	88	88.82
60	82	89.39	102	106.65	95	94.28
70	88	94.63	107	111.90	101	99.70
86	98	102.90	119	120.20	112	108.25

T amb [°C]	Difference [°C]	Difference [%]	Difference [°C]	Difference [%]	Difference [°C]	Difference [%]
27	6.81	10.48	8.00	9.88	1.40	1.87
42	7.86	10.92	7.14	7.93	1.41	1.70
50	8.11	10.67	6.45	6.79	0.82	0.93
60	7.39	9.01	4.65	4.56	-0.72	-0.76
70	6.63	7.53	4.90	4.58	-1.30	-1.29
86	4.90	5.00	1.20	1.01	-3.75	-3.35

Fig 14. Comparison between measurements and simulations for different ambient temperatures

The correlation between measurements and modeling is quite good; the difference is lower than 10 %.

With the simulation it's possible to simulate the influence of the glue thickness to fix the thermocouple. This influence is around 5 °C to 10 °C (for a measurement around 100 °C).

6. Conclusions

It's possible to get good simulations results if the environment is well known. The biggest difficulty is to define the convection coefficient and to model correctly the transistor. For the convection coefficient, several simulations could be done with different coefficient. The influence of the coefficient is quite important. For example we simulate a die temperature, for an ambient of 70 °C, of 115.6 °C with a coefficient of 13 [W K^{-1} m^{-2}] and 122.3 °C with a coefficient of 6.5 [W K^{-1} m^{-2}]. Following the detail of the transistor model, it's possible to reach good results in the transistor. For the transducer application, the model of the transistor used is enough accurate.

By simulation it has been possible to evaluate to evaluate the hot spot measurement error introduce by the glue used to fix the thermocouple; this effect, by far not negligible, makes the measurements difficult thus differences between calculation and measurements are for sure not only due to calculation inaccuracy.

Once the simulation is validated, the advantage of the thermal model is the flexibility and the rapidity to change the parameters (primary current DC or AC, ambient temperature, primary conductor temperature, …).

Time required to make the model and validate the simulation was approximately 3-4 weeks for futures similar products the prototype will not be required and approximately 1-2 weeks of engineering time is expected to complete a similar work.

The logical next steps would be the model of the iron losses for high frequency and the transient thermal simulation.

7. References

[1] *Current transducer – Thermal modeling by finite element, B. Richard. PCIM 2004, Nüremberg, Germany*